Ground-ground Optical Communications Demonstration

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- Introduction
- Experimental configuration & operations scenario
- Validated link analysis predictions
- Characterized atmospheric channel
- Characterized Optical Communications Demonstrator (OCD) performance
- Characterized overall link performance
- Conclusions & Future Work

Introduction

- Deep space optical communications road map calls for an incremental set of systems level demonstrations for validating technologies
  - Ground-ground optical links are the first set of cost-effective demonstrations conducted in June 1998

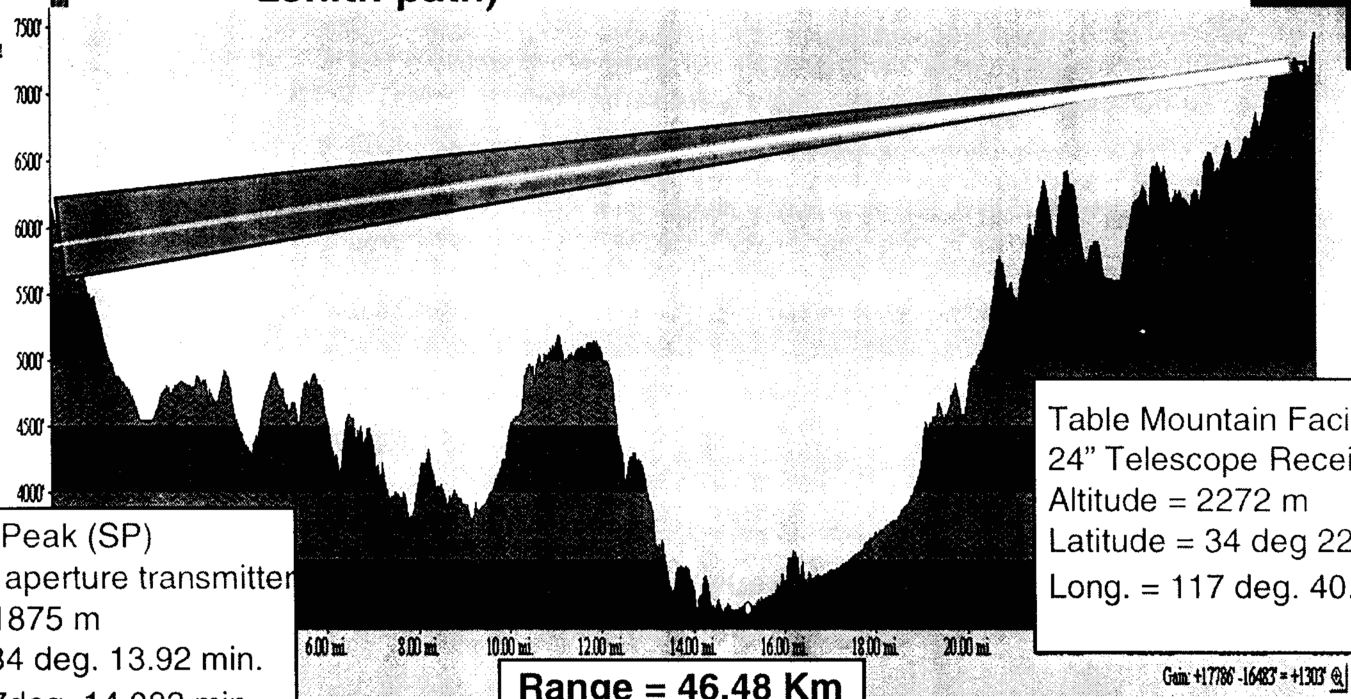
- Important to recognize the following about terrestrial horizontal path optical links
  - Horizontal path involves laser beam propagation through greater air-mass than space-ground links thereby compounding the atmospheric channel effects on link
  - Optical transmitter immersed in atmosphere, resulting in considerable beam wander **not** expected in ground-to-space links

- Therefore, while the extent of performance validation is limited, valuable insight and experience is derived from terrestrial link demonstrations

Ground-ground Optical Communications Demonstration

Configuration used for Strawberry Peak (SP) to Table Mountain Facility (TMF) Link

(At least 4 times the air mass for equivalent zenith path)

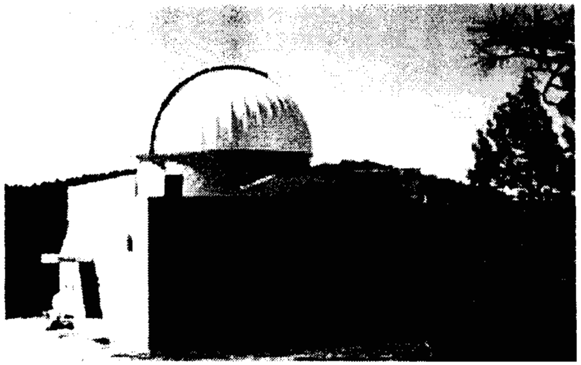


Strawberry Peak (SP)
OCD 10cm aperture transmitter
Altitude = 1875 m
Latitude = 34 deg. 13.92 min.
Long. = 117deg. 14.083 min.

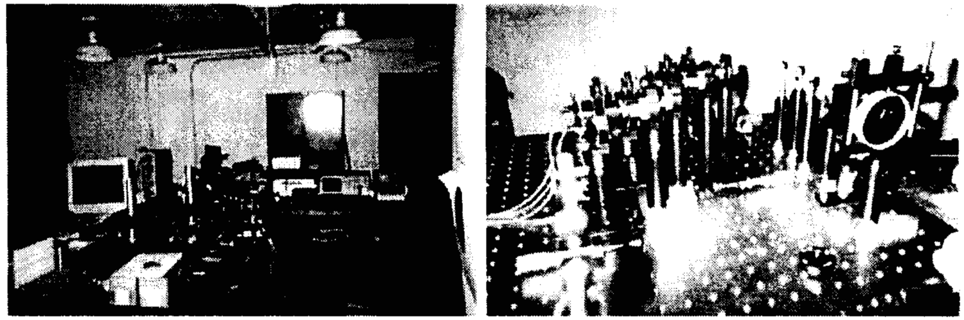
Range = 46.48 Km

Table Mountain Facility (TMF)
24" Telescope Receiver
Altitude = 2272 m
Latitude = 34 deg 22.9 min
Long. = 117 deg. 40.897 min.

Ground-ground Optical Communications Demonstration

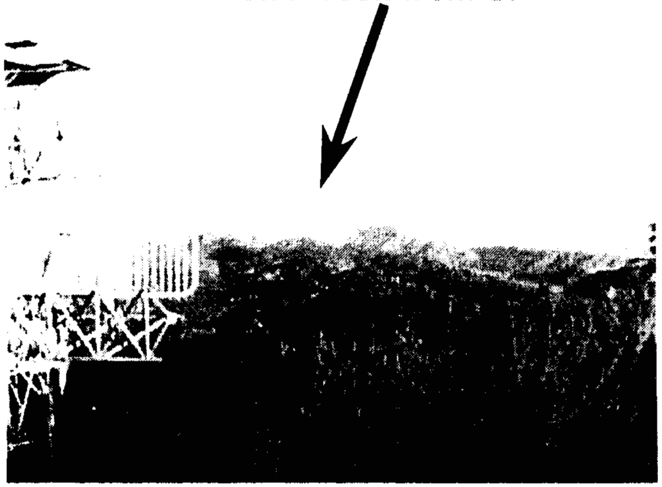


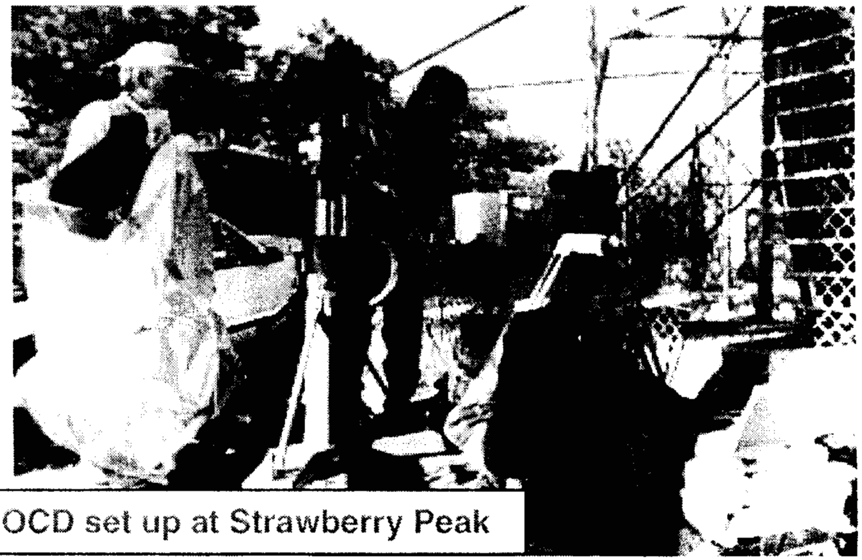
TMF 0.6 m telescope used as receiver



Coude Room Optical Assembly

TMF seen from SP





OCD set up at Strawberry Peak

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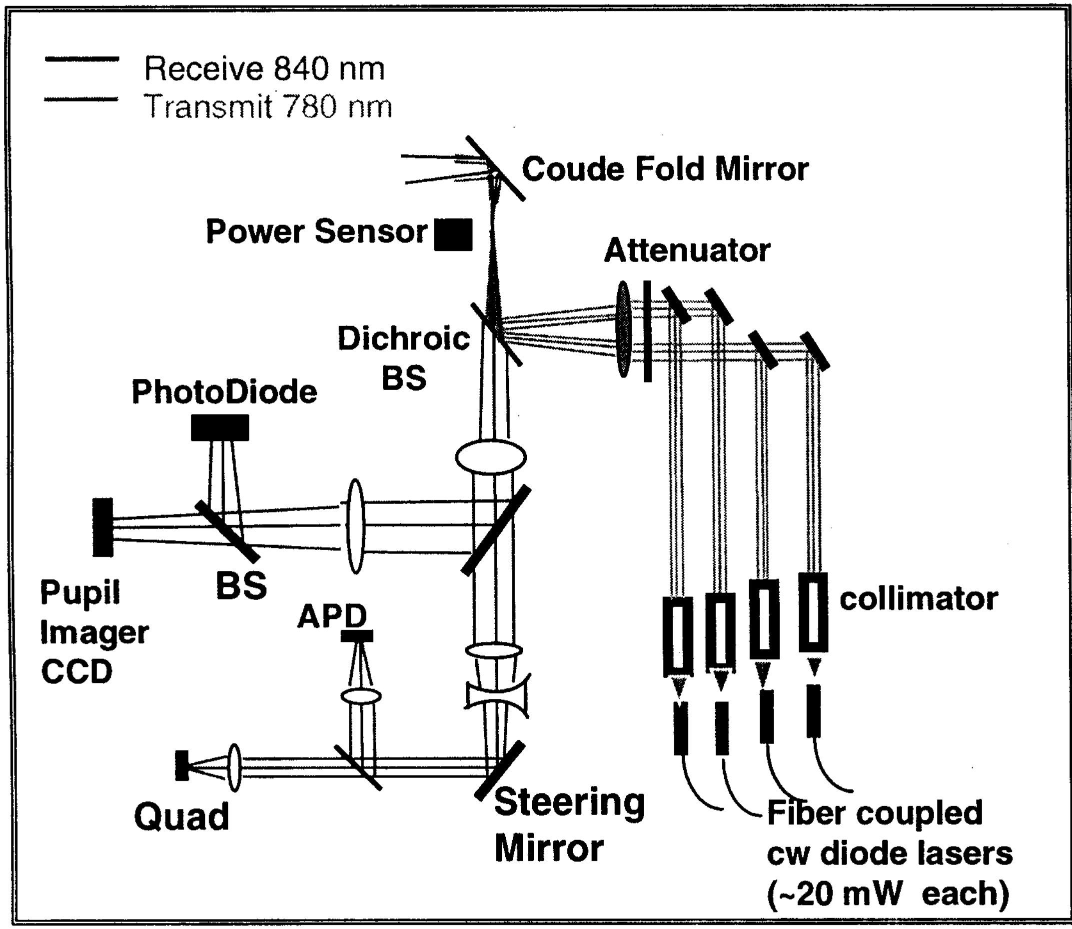
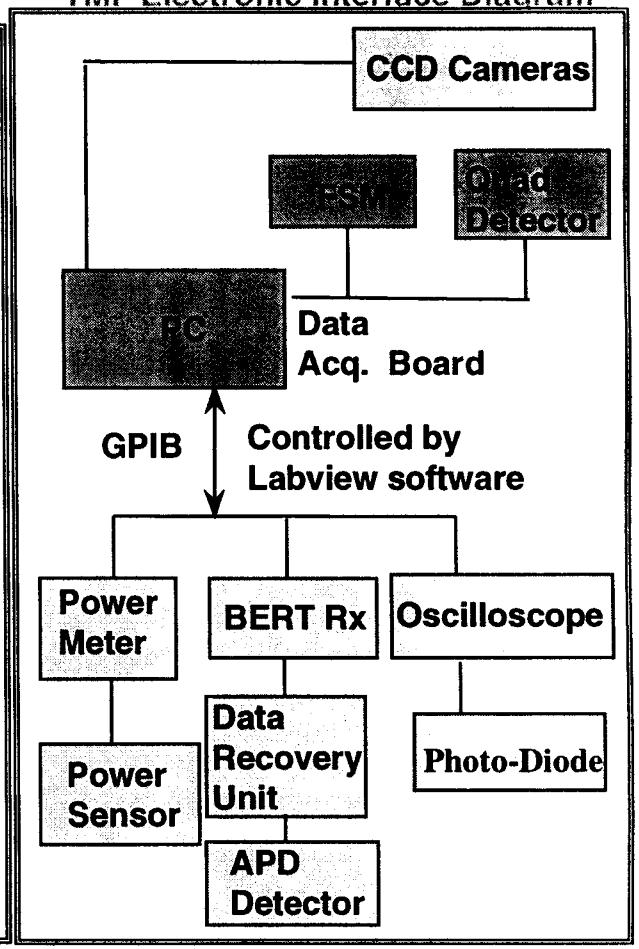
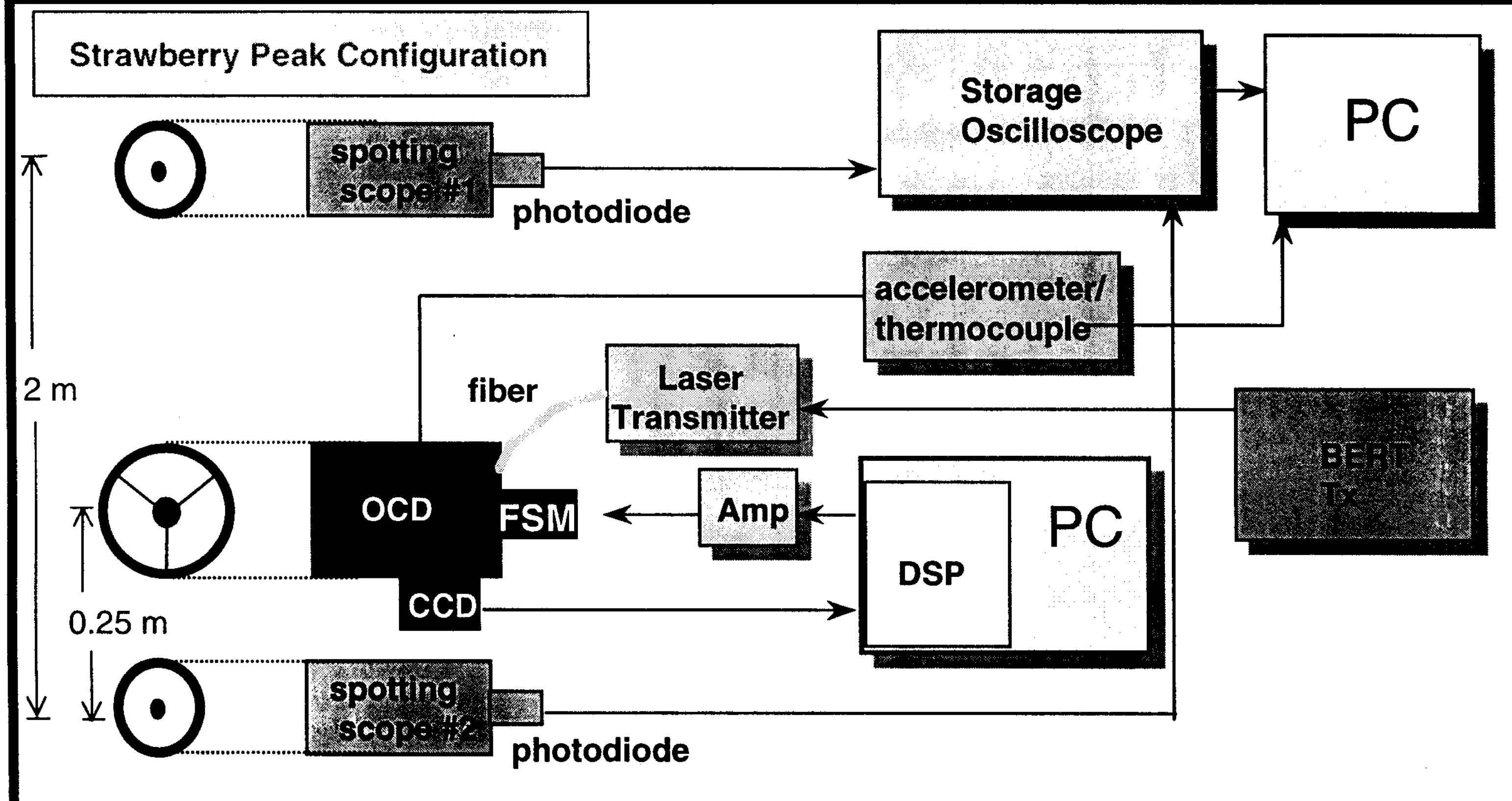
TMF Transmit/Receive Optical Assembly



TMF Electronic Interface Diagram



Ground-ground Optical Communications Demonstration



Spotting scopes used to monitor intensity fluctuations of received beacon signal

Operations Scenario

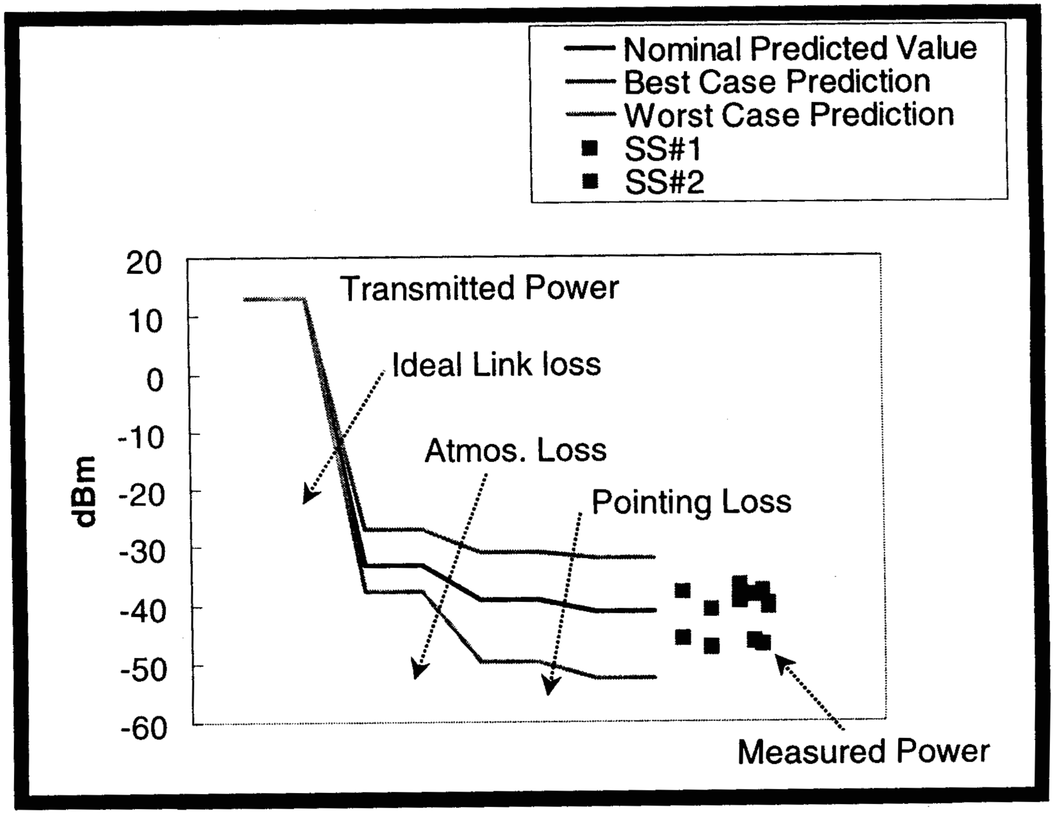
- Transmitted beacon laser from Table Mountain Facility (TMF) to Strawberry Peak (SP)
- Acquired beacon laser using Optical Communications Demonstrator (OCD) at SP using manual coarse pointing
- Transmitted OCD laser beam back to TMF to confirm transmit-receive co-alignment
- Performed the following at SP
  - used spotting scopes to monitor average beacon power and perform scintillation measurements on beacon
  - used OCD to acquire beacon spot images and centroid
  - activated closed loop fine tracking and logged tracking data on OCD
- Performed the following at TMF
  - monitor received power and scintillation at TMF
  - monitor focussed spot size and pupil image at TMF
  - record communications signal eye-patterns and BER

LINK ANALYSIS TMF TO SP AND RECEIVED POWER AT SP

- Validated link predictions using average signal power for each beacon diode laser transmitted from TMF

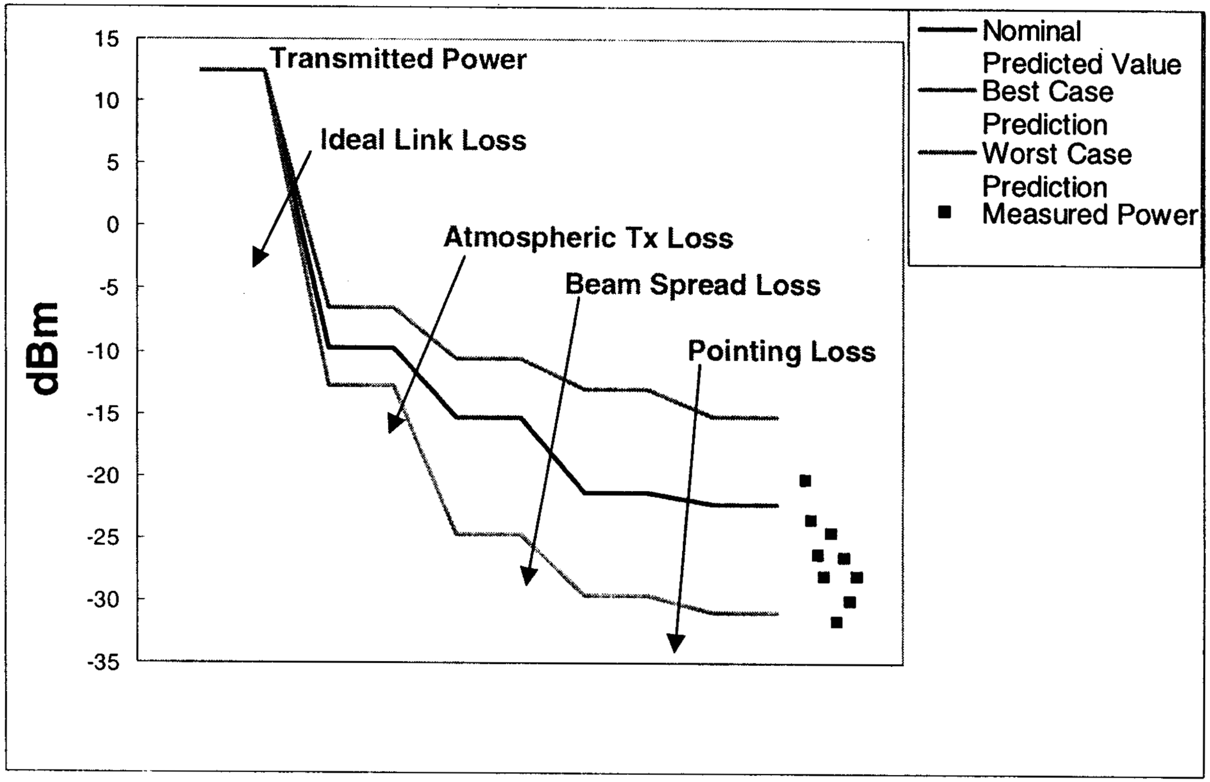
- Spotting scope closer to OCD (SS#2) measured 5-7 dB higher average power

- Based on angular separation of the SS#1 and SS#2 the measured difference is consistent with ~ 70 μrad of beam divergence compared to the designed 100 μrad



LINK ANALYSIS SP TO TMF AND RECEIVED POWER AT TMF

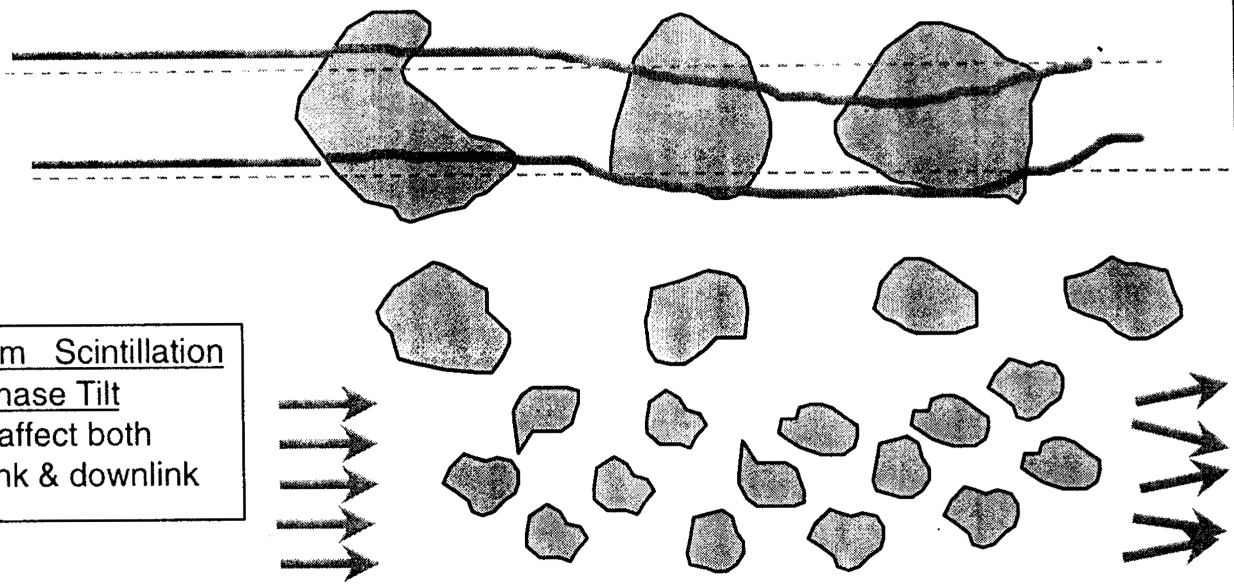
- **Validated link predictions using average signal power measured at TMF**



Atmospheric Channel

- **Deep space optical links to earth receivers will involve transmission of uplink and downlink laser beams through an atmospheric path**

- **In addition to cloud-free atmospheric attenuation due to absorption and scattering thermally induced refractive index fluctuations impact link performance**



Beam Wander
- Beam footprint must be ~ atmospheric cell size.
- While in terrestrial links this effects both beams
- In space-ground links will affect only uplink

Beam Scintillation & Phase Tilt will affect both uplink & downlink

Atmospheric Channel

- **Optical communications laser beams are subjected to intensity fluctuations as a result of traversing the turbulent atmosphere**

- **Intensity fluctuations are characterized by**

$\sigma_I^{\ 2} = \langle I^2\rangle/\langle I\rangle^2 - 1$ *scintillation index σ_I^2*

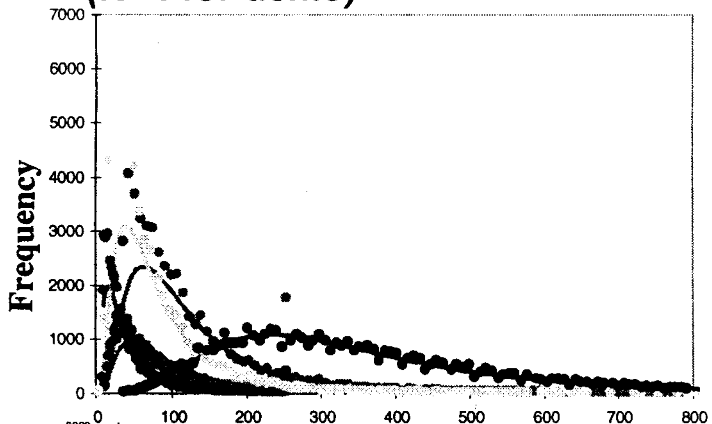
$\sigma_I^{\ 2} < 0.5$ **weak fluctuation**	**$1 > \sigma_I^{\ 2} > 0.5$ strong fluctuation**	**$\sigma_I^{\ 2} = 1.0$ saturation**

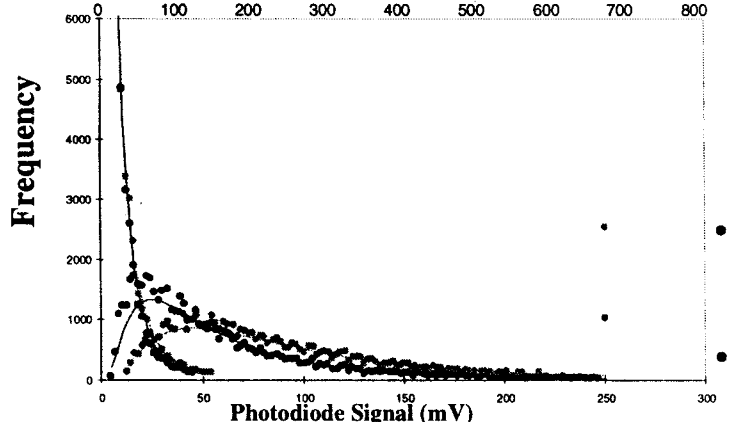
- **Well developed and validated theories exist for the "weak fluctuation" regime for "strong fluctuation" region some approximate theories exist which are not well validated**

- **Optical communications links must find a means of mitigating atmospheric effects by effectively reducing the scintillation index**

Multi-Beam Beacon Scintillation Measurements TMF to SP

- ***scintillation index of N beams should decrease as 1/N (N=4 for demo)***





- **Measured σ_I^2 values show reduction**
  - -deviation from predicted values due to imperfect co-alignment of the four beams

Single Beams		4- Beams
Beam 1	0.50	0.22 (0.17 predicted)
Beam 2	0.82	
Beam 3	0.68	
Beam 4	0.73	

→ **on-axis** measurements

Single Beams		4-Beams
Beam 1	1.04	0.34 (0.20 predicted)
Beam 2	0.76	
Beam 3	0.75	
Beam 4	0.72	

→ **off-axis** measurements

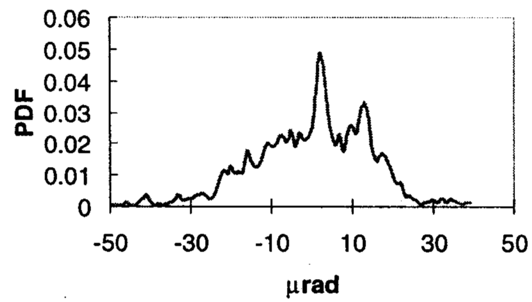
- **Measured <u>on-axis</u> versus <u>off-axis</u> difference in σ_I^2**
  - difference larger than predicted by Gaussian beam theory
- **Reduction in σ_I^2 translates reduction in dynamic range from 17-22 dB to 12-13 dB**

Atmospheric Channel Effects on Optical Communications

- **The spot acquired by OCD tracking sensor showed varying size from 40-100 μrad compared to 20-30 μrad seen in laboratory**
  - this compares to 28-95 μrad prediction

- **Probability distribution function shows a 60 μrad motion in beacon centroid**
  - this motion far exceeds predicted ~30 μrad of angle of arrival fluctuation

Acquired Beacon Spot by OCD Tracking Sensor



OCD Fine Tracking

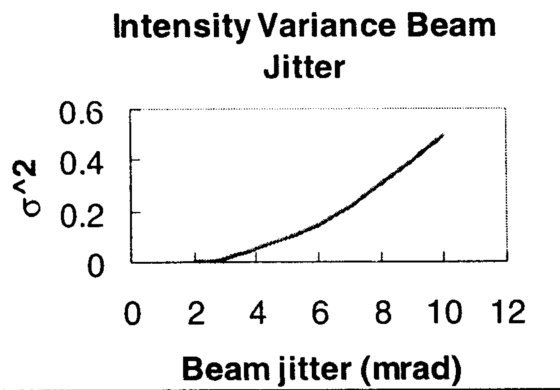
- **Tested OCD fine tracking performance with both transmitter and receiver stationary but atmospheric perturbations causing beacon spot to move**
- **Tracking was achievable using the OCD fine tracking loop, however, the lock was intermittent**
  - primary cause of loss of track was beacon fades sensed by the OCD focal plane CCD
  - the CCD dynamic range (10 dB) is inadequate for level of beacon intensity fluctuation measured 12-14 dB
  - could determine the uncompensated tracking for fade free durations
- **Uncompensated tracking error was measured to be ~ 8 μrad compared to 2 μrad measured in laboratory, the degradation is attributed to**
  - the beacon spot enlargement contributes to inaccuracies of centroid
  - the OCD loop 3 dB bandwidth is 60 Hz thus all atmospheric components are not compensated
- **Preliminary OCD tracking characteristics, obtained between 12:00 AM to 4:00 AM on June 19, 1998**
  - tracking error 1σ is ~ 8 μrad
  - beacon tracked over at least 10 dB dynamic range
  - normalized intensity variance measured by OCD CCD was 0.15 compared to independently measured beacon fluctuation of 0. 22
  - average 0.06 fades per second observed over 1000 seconds

Ground-ground Optical Communications Demonstration

JPL

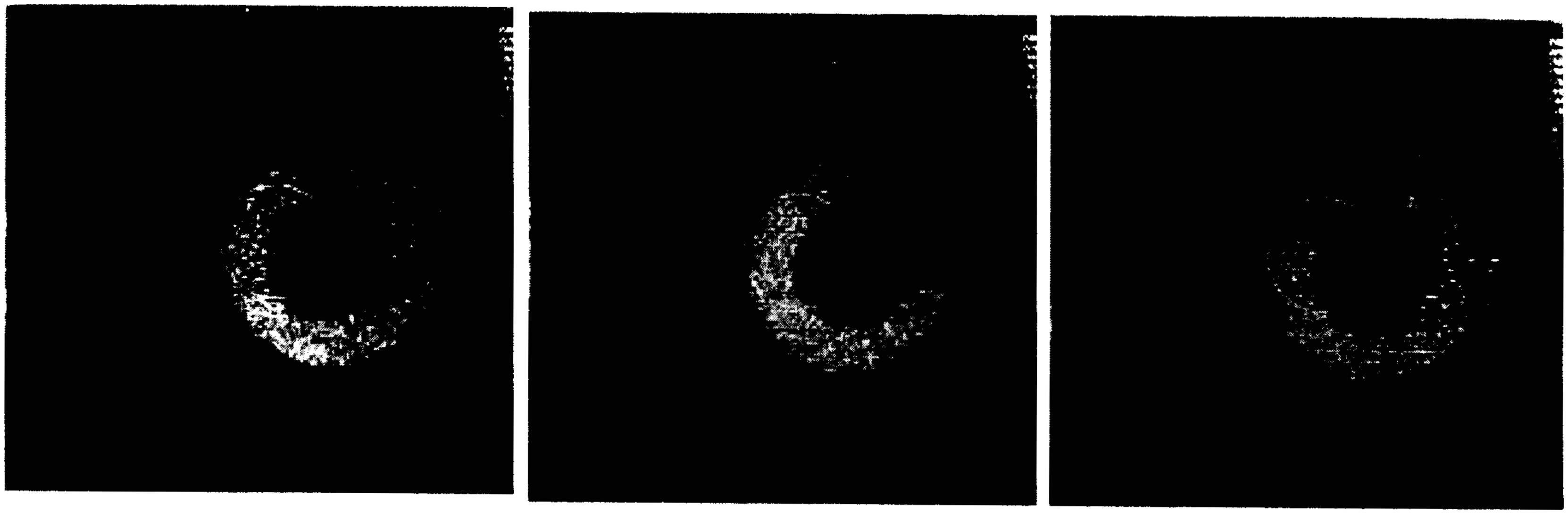
Communications Performance

- **Measured OCD beam footprint received at TMF was 1.67 m compared to expected 1.2m**
  - appearance of beam footprint is more elliptical than circular with the minor axis shorter perpendicular to direction of propagation
- **In absence of OCD fine tracking the beam the OCD footprint received at TMF exhibits wander of of 4 m**
  - maximum beam wander predicted by theory is 1m
- **Measured scintillation index σ_I^2 on the communications signal returned to TMF to be 0.43 whereas the expected value with aperture averaging taken into account was <0.1**



- **analysis shows that additional beam jitter may be a possible cause for the worse than expected scintillation**

- **Examples of recorded pupil image display the expected speckle caused by phase front perturbations of laser beam wavefront**



- **Atmospheric "seeing" and coherence length**

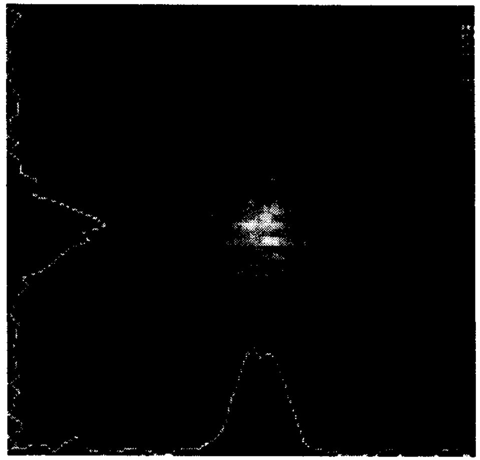
Plane Wave

- spatial coh. length < inner scale r0 =3.6 cm, expected spot size 172 µm, seeing - 4-5 arcsec
- spatial coh. lenght > inner scale r0 = 7 cm, expected spot size 91 µm, seeing - 3 arcsec

Gaussian Wave

- spatial coh. length < inner scale r0 =6.2 cm expected spot size 100 µm, seeing ~3.2 arcsec
- spatial coh. lenght > inner scale r0 = 12.2 cm expected spot size 52 µm, seeing ~1.6 arcsec

Measured focal spot size was 162 +/- 6 mm



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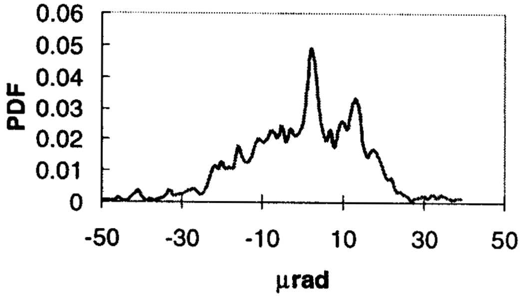
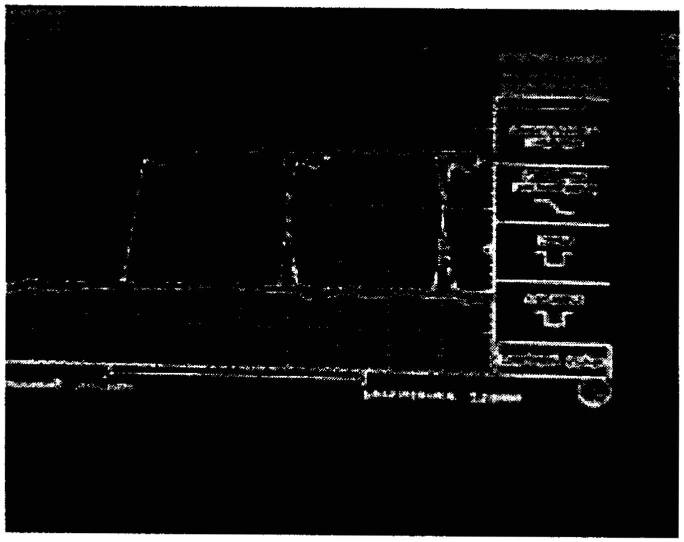
Acquired Beacon Spot by OCD Tracking Sensor





- **Acquired beacon spot motion on OCD CCD**

- **OCD fine tracking features**
  - tracking error 1s is ~ 3.3 mrad (lab 1.7 mrad)
  - beacon tracked over at least 10 dB dynamic range
  - average 0.06 fades per second observed over 1000 seconds

- **Obtained lock for 10's of seconds to minutes with loss of lock attributed primarily to atmosphere induced fades**

- **Eye-pattern measured @ 325 Mbps**

Conclusions

- **Validated link analysis uncertainties for bi-directional horizontal path link**
- **Investigated intensity fluctuations on either side of link**
  - showed intensity distributions
  - verified multi-beam scintillation reduction and obtained preliminary data on effect of mis-pointing
  - showed that for our experimental parameters aperture averaging does not take care of scintillation most probably due to beam jitter effects
- **Investigated other atmospheric effects**
  - atmospheric coherence length measurements nominally obey predictions
  - beam wander and angle of arrival fluctuations predictions are lower than measurements
- **Reported on preliminary OCD ack/trk performance**
  - need further testing to characterize
- **Showed BER and eye-pattern measurements 1E-5 averaged over 1 sec**